Design of Exposure Systems and Bioagent Inactivation Devices: Aerosol Generation, Measurement and Characterization

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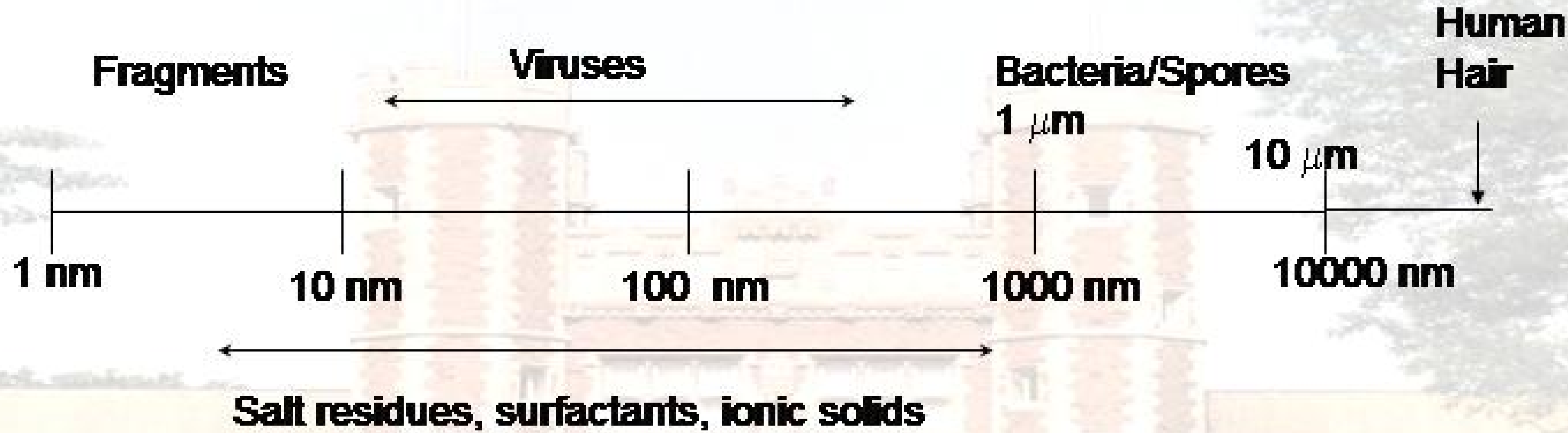
Outline of Presentation

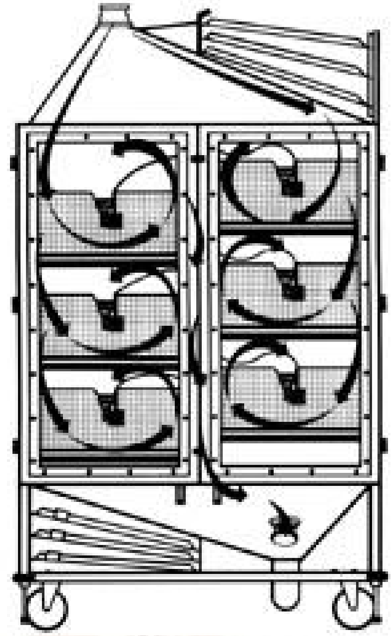
- Aerosol Generation
- Aerosol Measurement for bacteria and viruses; protein molecules and fragments.
- Characterization of Exposure Chambers - are the aerosols well distributed, flow modeling, transport in respiratory system and deposition
- Inactivation of Bioagents in Airborne Streams - just brief mention.

EVEN BIOAEROSOLS COVER A BROAD RANGE



PHYSICS OF TRANSPORT, GROWTH

- Size (aerodynamic size?, shape is also important)
- Concentration (number based metric, # / cm^3)
- Morphology – shape, agglomerate state
- Biological particles generally carry a surface charge, very important
- Other surface characteristics – hydrophobic, hydrophillic, etc.



EXPOSURE CHAMBER

AEROSOL GENERATOR

AEROSOL MEASUREMENT

OTHER IMP. CONSIDERATIONS
- Transport Modeling
- Aerosol dynamics (size change)
- Resipratory Deposition

Aerosol Generation

- **Aerosolize suspension in liquid without changing viability (considerations: fragmentation, charge distribution, etc)**
- Role of other constitutents – surfactants, ionic salts, etc.
- Resultant throughput and size distribution

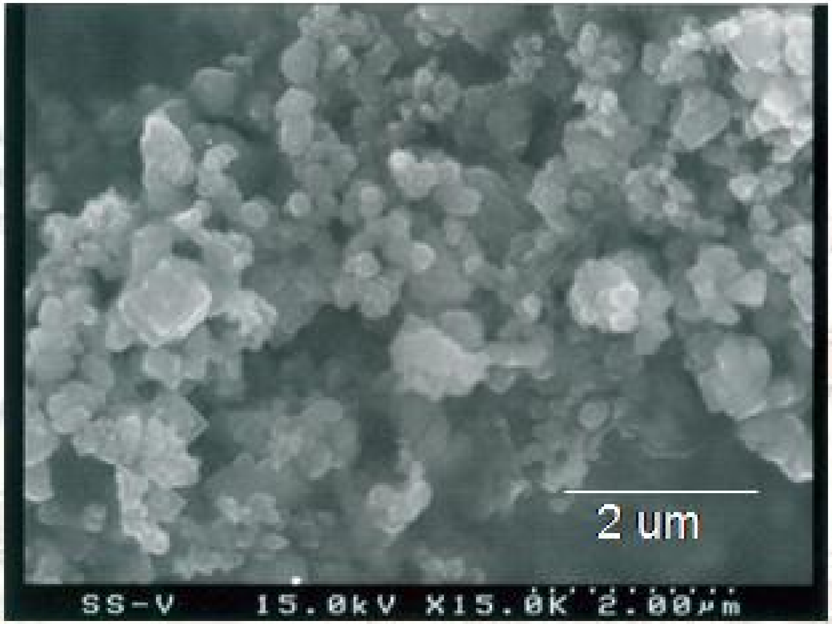
ATOMIZATION

- Uses a high velocity air jet to create a pressure difference that pulls liquid w/suspension from a reservoir
- Air jet breaks up liquid stream into droplets
- Impaction results in size selectivity – only smaller droplets are aerosolized. Larger droplets drop back into reservoir
- Possible disadvantage: damaging of organism on impaction. Re-design will result in gentler impaction, and non-reuse of larger droplets generated

NEBULIZERS

- Similar principle as atomizer – gentler aerosolization
- Can have higher throughputs, lesser control on size
- Designs (such as BANG, etc to minimize foaming)

SEM images of MS2 bacteriophage (polio virus surrogates) aerosolized with a Collison Nebulizer



(a) Virion particles in suspended solution

(b) Virion particles after nebulizer

Nebulized Particles Tend to Clump Together !

Hogan, Lee, Biswas (2003) In review, *Aerosol Sci. Technol.*

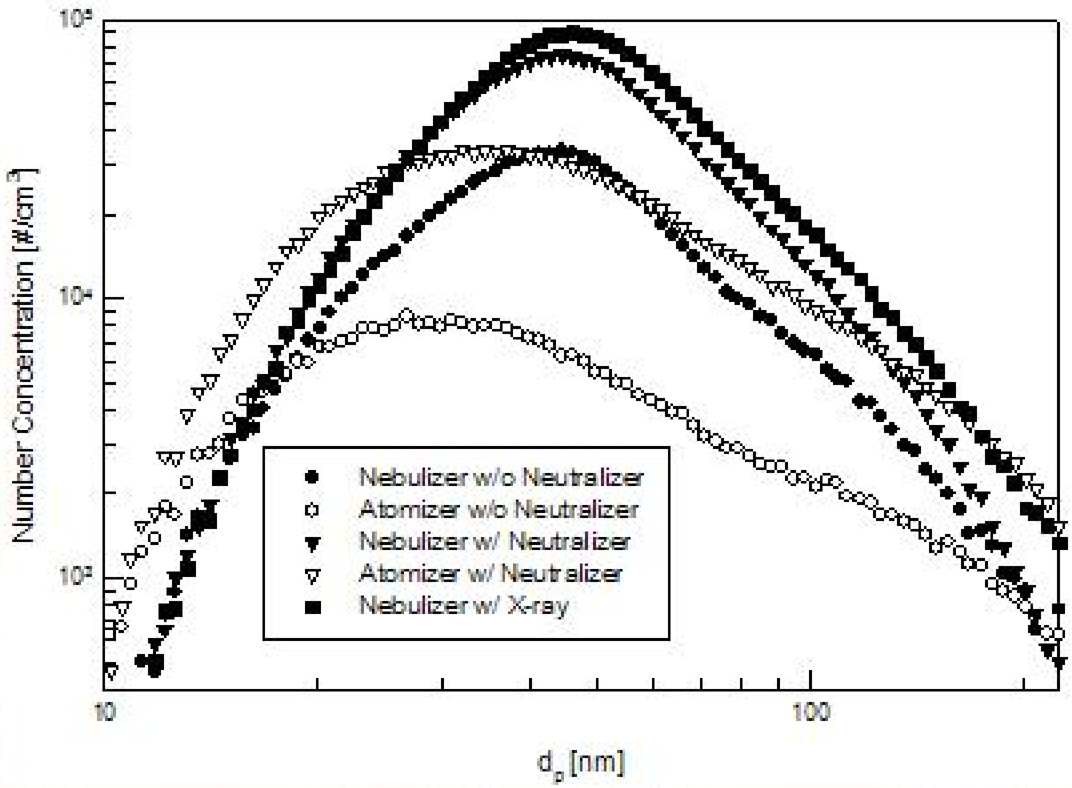
Though the viral particles are 25 nm in diameter, we measure a broader size distribution

Smaller particles are due to fragments of the particles – either due to nebulization or due to breakup as a result of surface charges

Larger particles due to tendency to aggregate

Our systems have allowed us to conduct fundamental studies on charge distributions on these viral particles – NEVER DONE BEFORE.

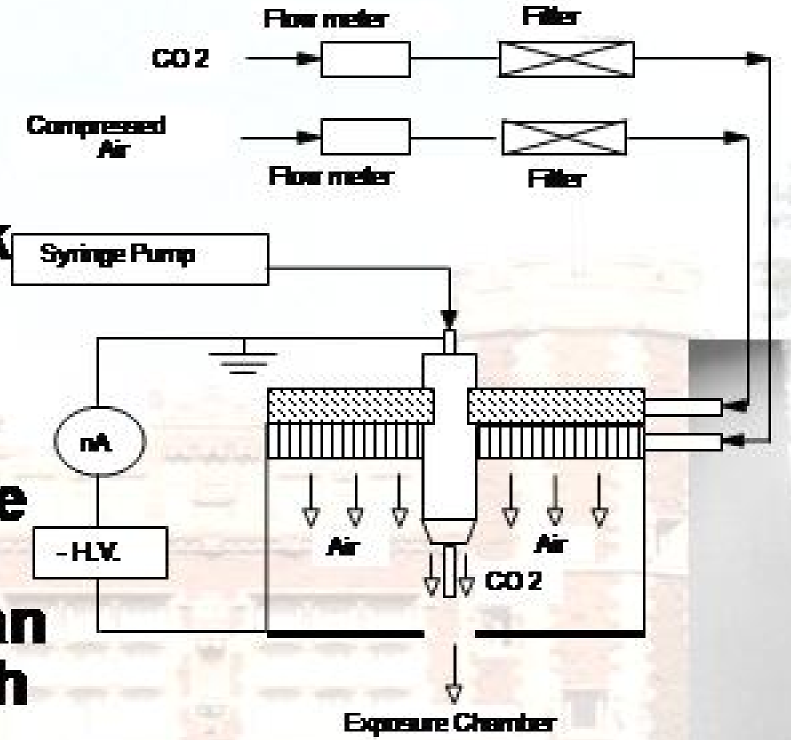
Why are such fundamental studies Important? – To better design control methodologies, scale up, ensure byproducts are not formed

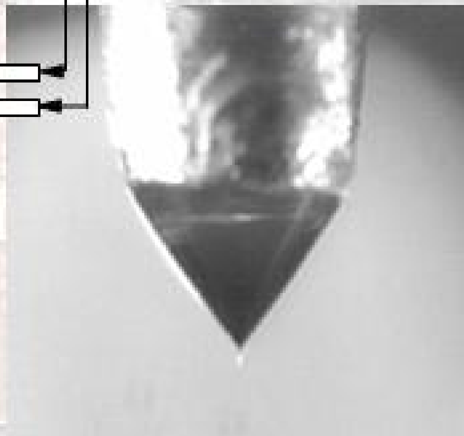


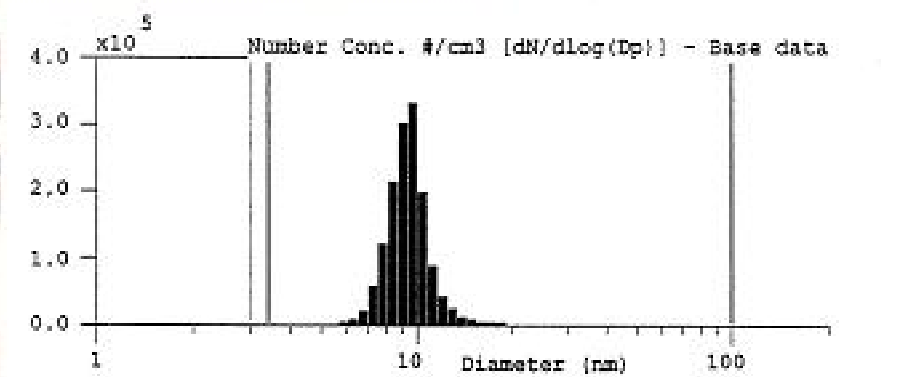
REAL TIME MEASUREMENT OF VIRAL PARTICLE SIZE DISTRIBUTIONS.

ELECTROSPRAYS

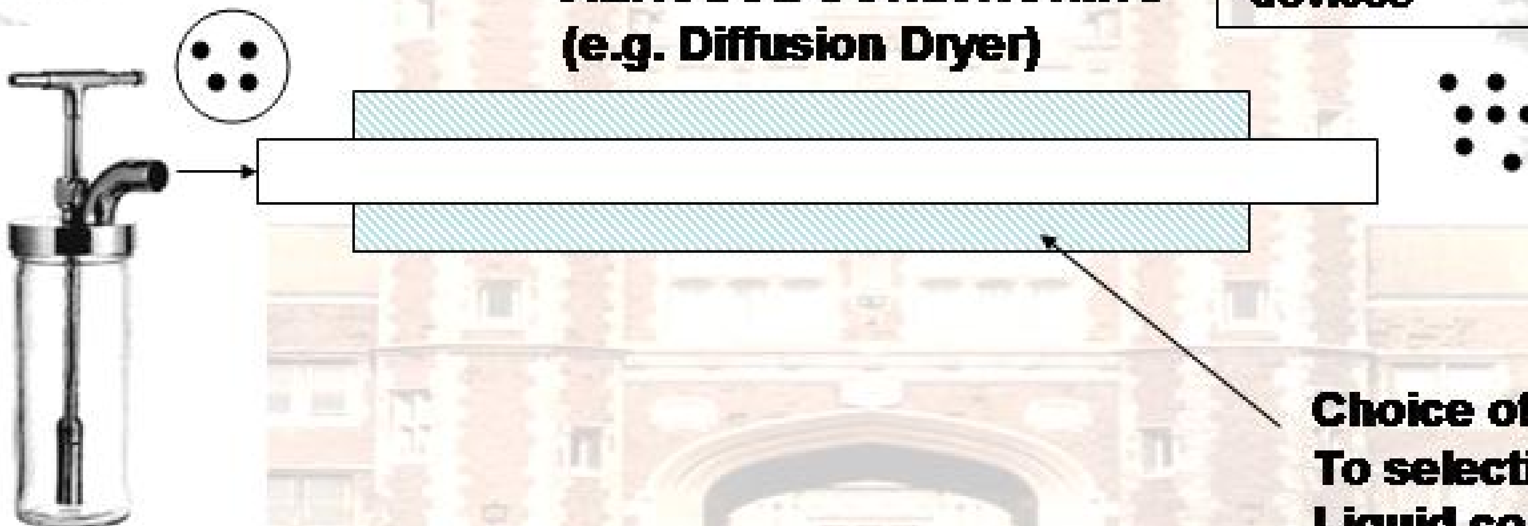
- **Use an applied electrical field to break up droplets**
- **Ability to manipulate size in very narrow ranges and hence state of the resultant particles (overcome van der Waals forces which tend to hold particles together causing clumping)**
- **Can eliminate role of other additives in the solutions**







POST GENERATION CONDITIONING



Summary of "Aerosol Generation"

- Nebulizers may not be able to produce single units of the bioagent; even if starting material is "ultra-pure". Atomizers maybe better in size control, but may alter viability
- Post conditioning is a viable means of obtaining a well characterized aerosol, and maybe essential
- Electrosprays one of the best ways of generating particles in a large range of sizes

Aerosol Measurement

- Real time instruments that measure size distributions
- Most reliable are the electrical mobility techniques – especially for particles in the submicrometer and nanometer size ranges
- Optical instruments based on light scattering are also feasible – need some prior knowledge of organisms
- As real time instruments are well developed, routine monitoring in chambers using probes are advisable

GOVERNING EQUATIONS OF PARTICLE MOTION

- Equations for transport
- External force fields – gravity, electrical forces
- Other modes of transport: diffusion
- Important non-dimensional parameters

$$m\frac{d\overline{v_p}}{dt} = \frac{3\pi\mu d_p}{C}\left(\overline{u} - \overline{v_p}\right) + \overline{F_{ext}}$$

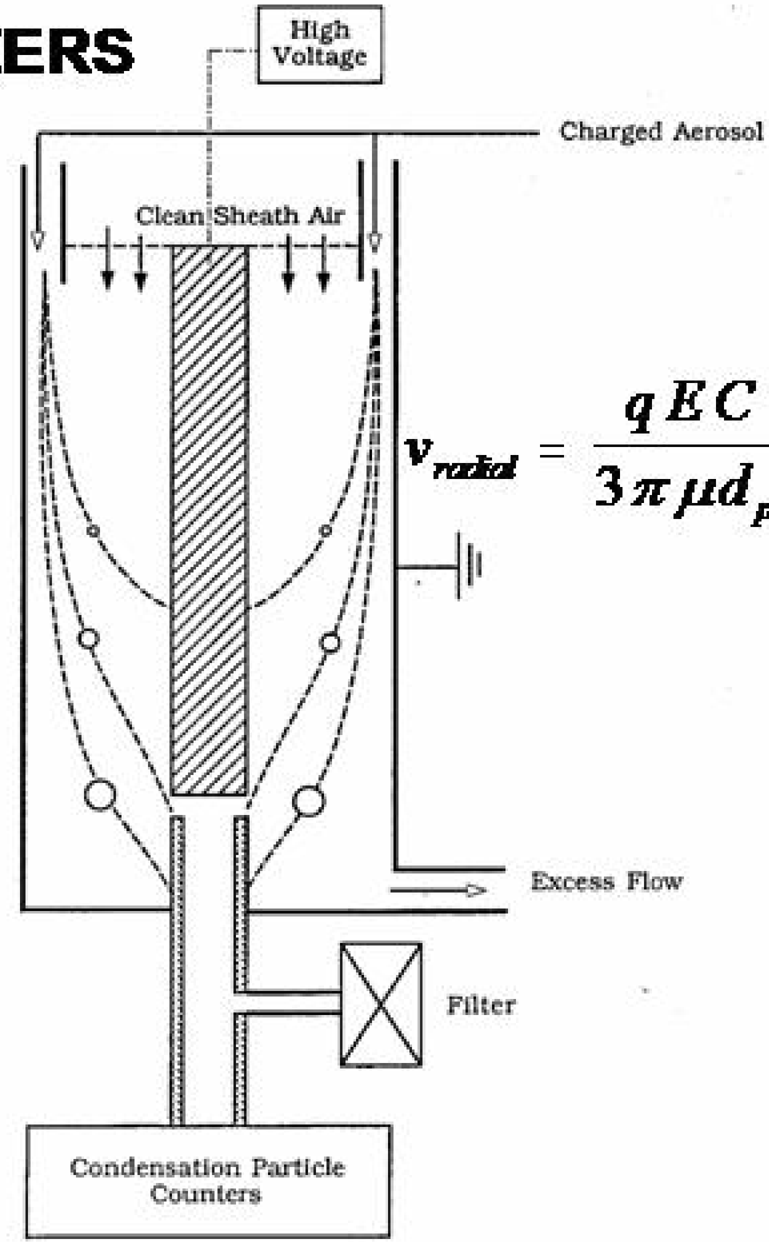
$$F_{electrical} = qE$$

$$D = \frac{kT}{3\pi\mu d_p} \quad ;\textit{Diffusion Coefficient}$$

$$St = \frac{\rho_p C d_p^{\,2} U_0}{18\mu L}$$

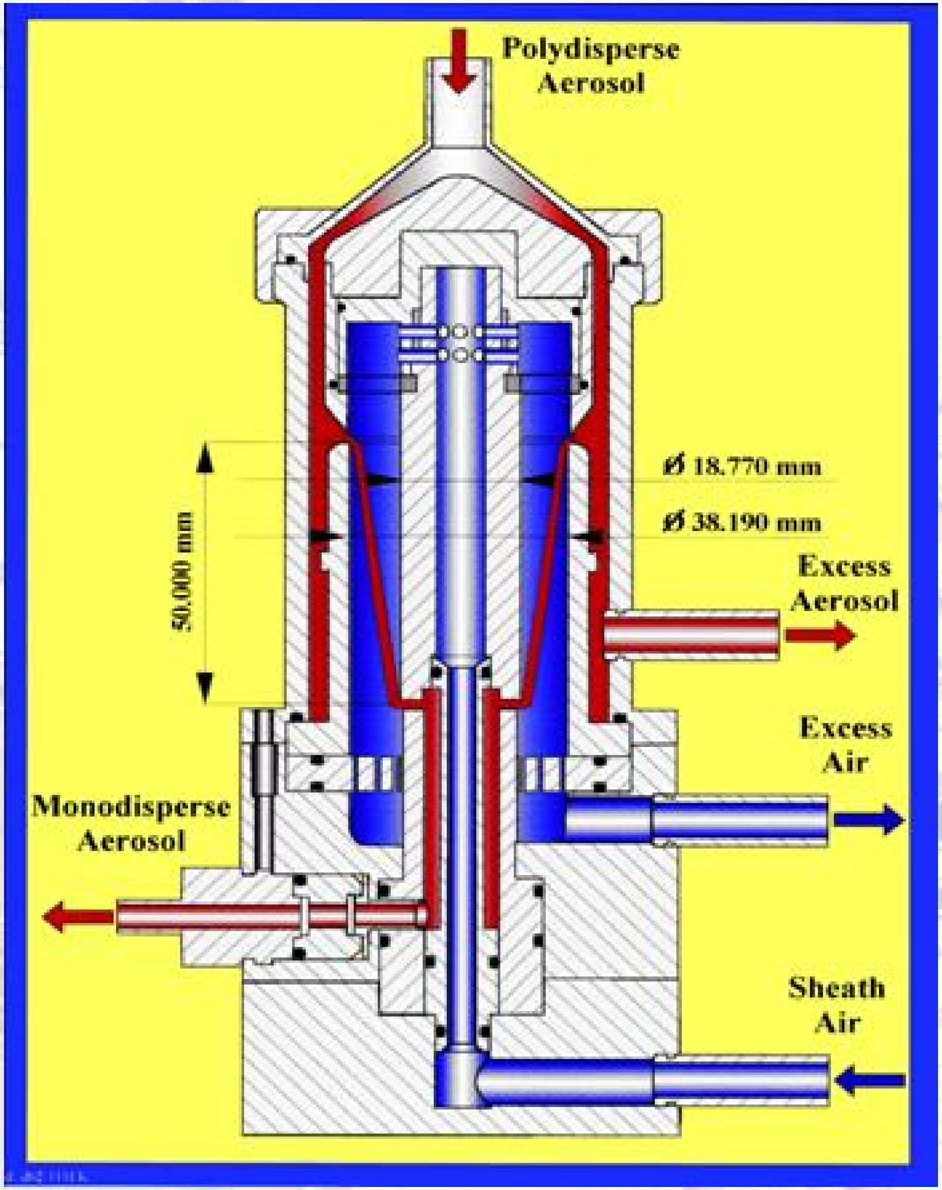
DIFFERENTIAL MOBILITY ANALYZERS

- Differential Mobility Analyzer – known charge on particles that are then classified in an electrical field
- Based on tuned electrical field (applied voltage) – a very narrow size of the particles can be selected
- The monodisperse stream can be used for further studies, or can be sent to a Condensation Particle Counter for counting
- Sequential change in voltage allows mapping the entire size distribution – Instrument called the Scanning Mobility Particle Sizer (SMPS)



$$v_{radial} = \frac{qEC}{3\pi\mu d_p}$$

Overall system layout (SMPS)

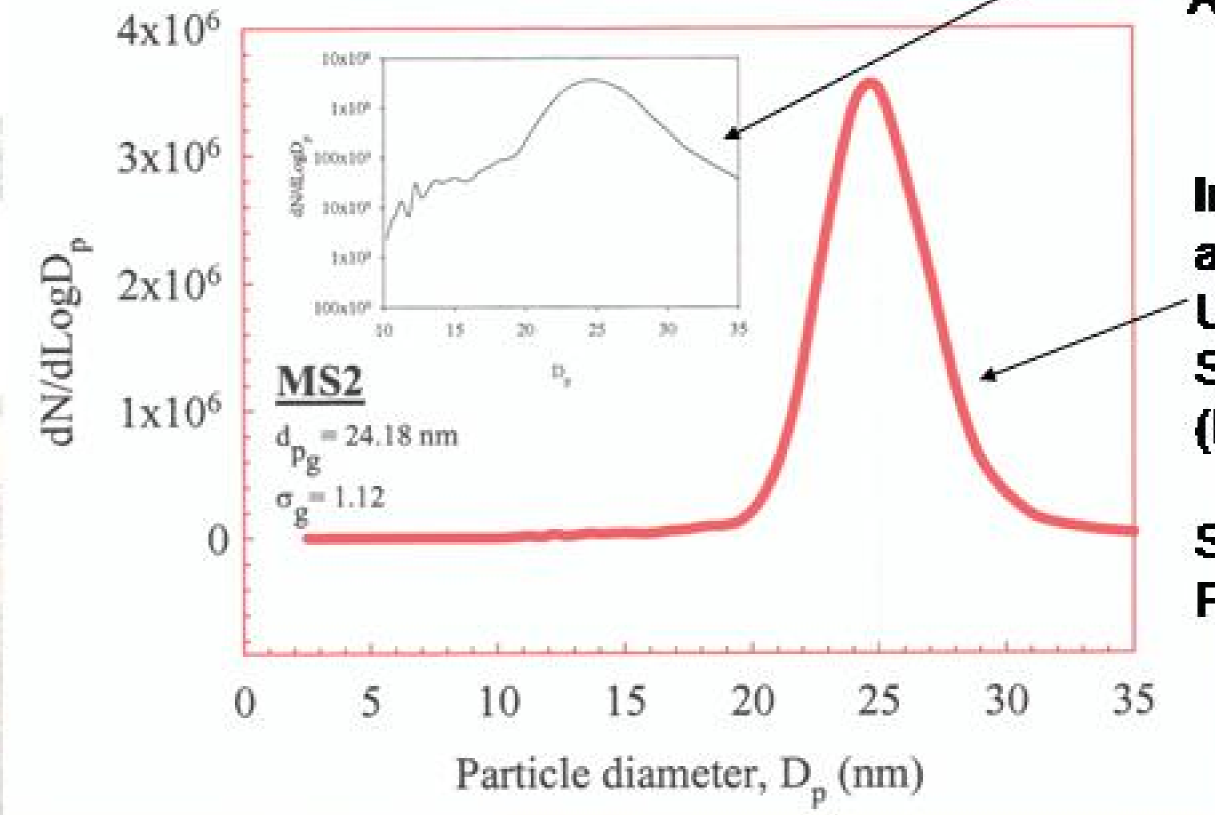


NANO - DMA

- Need to measure and classify real small particles – nanometer sized, such as viruses, protein fragments, etc
- Diffusion losses preclude effective measurement
- Modify DMA to minimize flight time and losses of nanoparticles – the NANO- DMA.

INSTRUMENTATION FOR QUICK DETECTION OF VIRUSES & PROTEIN FRAGMENTS

MS-2 BACTERIOPHAGE (POLIO VIRUS SURROGATE)



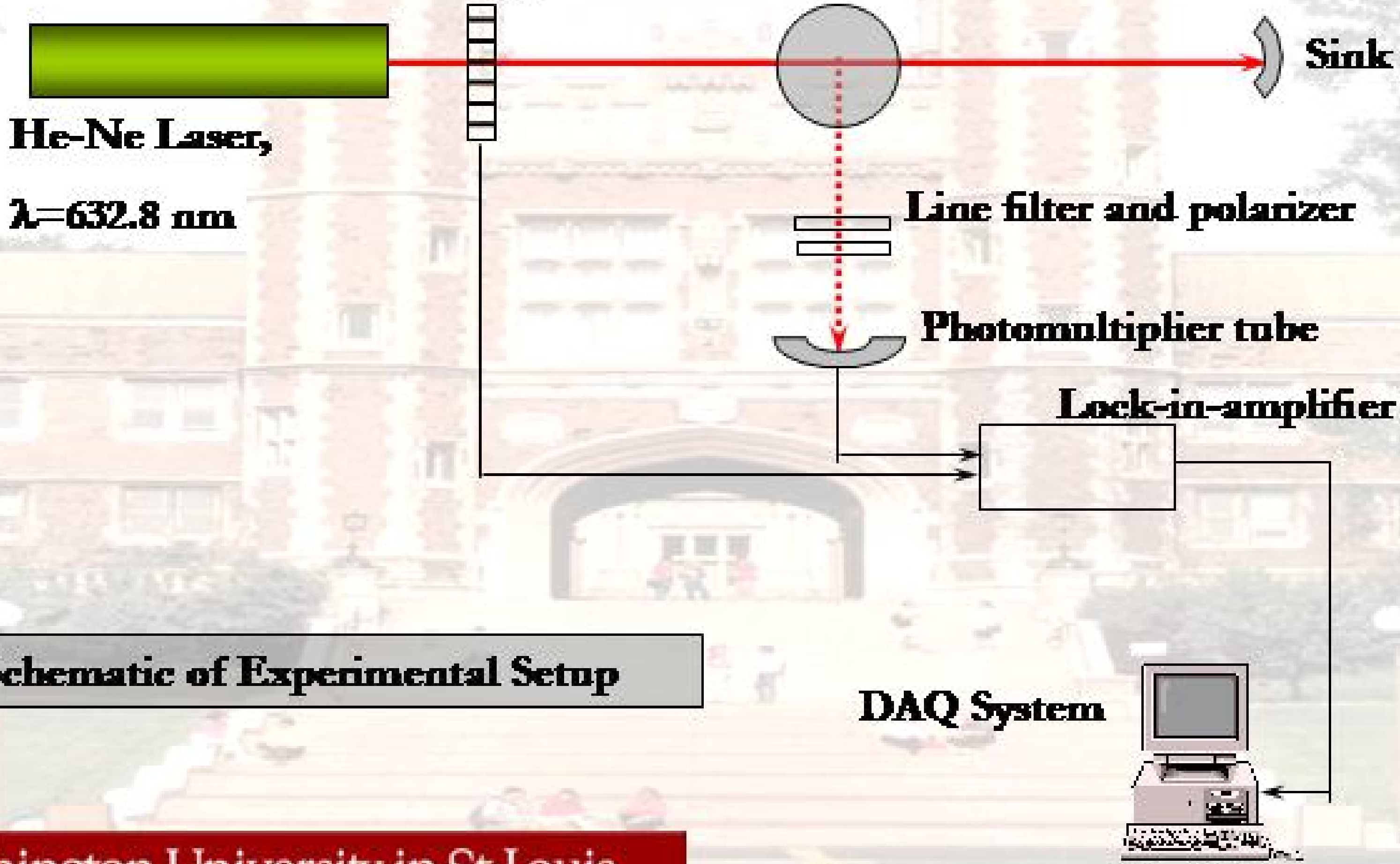
Routinely used atomizers And DMA

Improved accuracy, and reduced time, Using Electrospray System (Kulkarni, Chen, Biswas, 2003)

System can also measure Protein fragments - selectivity

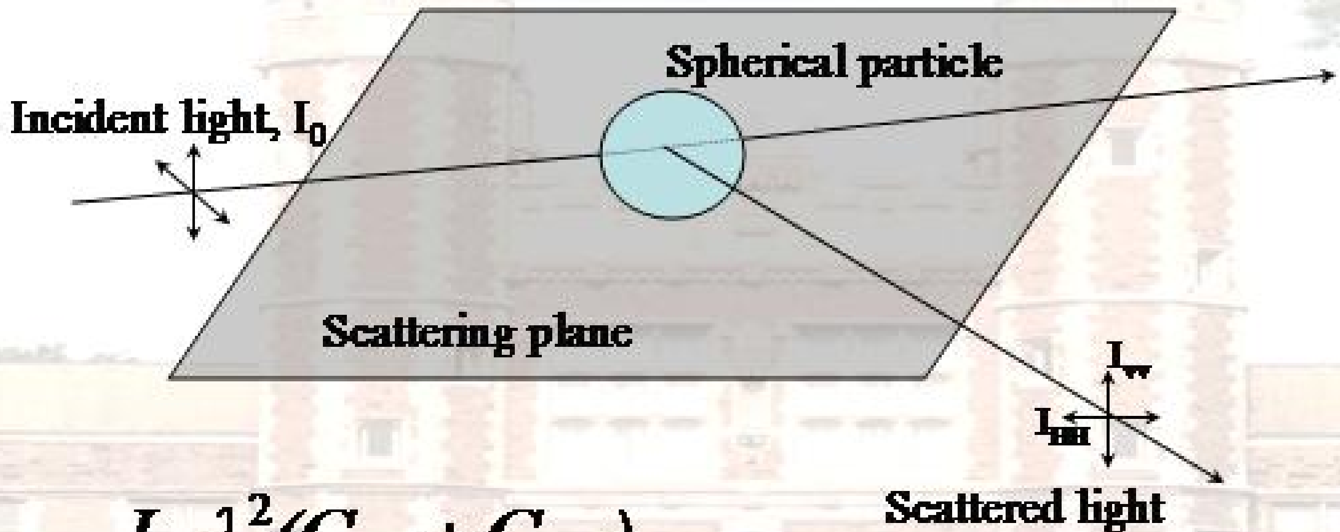
APPLY TO BIOAGENT DETECTION SYSTEMS

OPTICAL MEASUREMENT SYSTEMS



Schematic of Experimental Setup

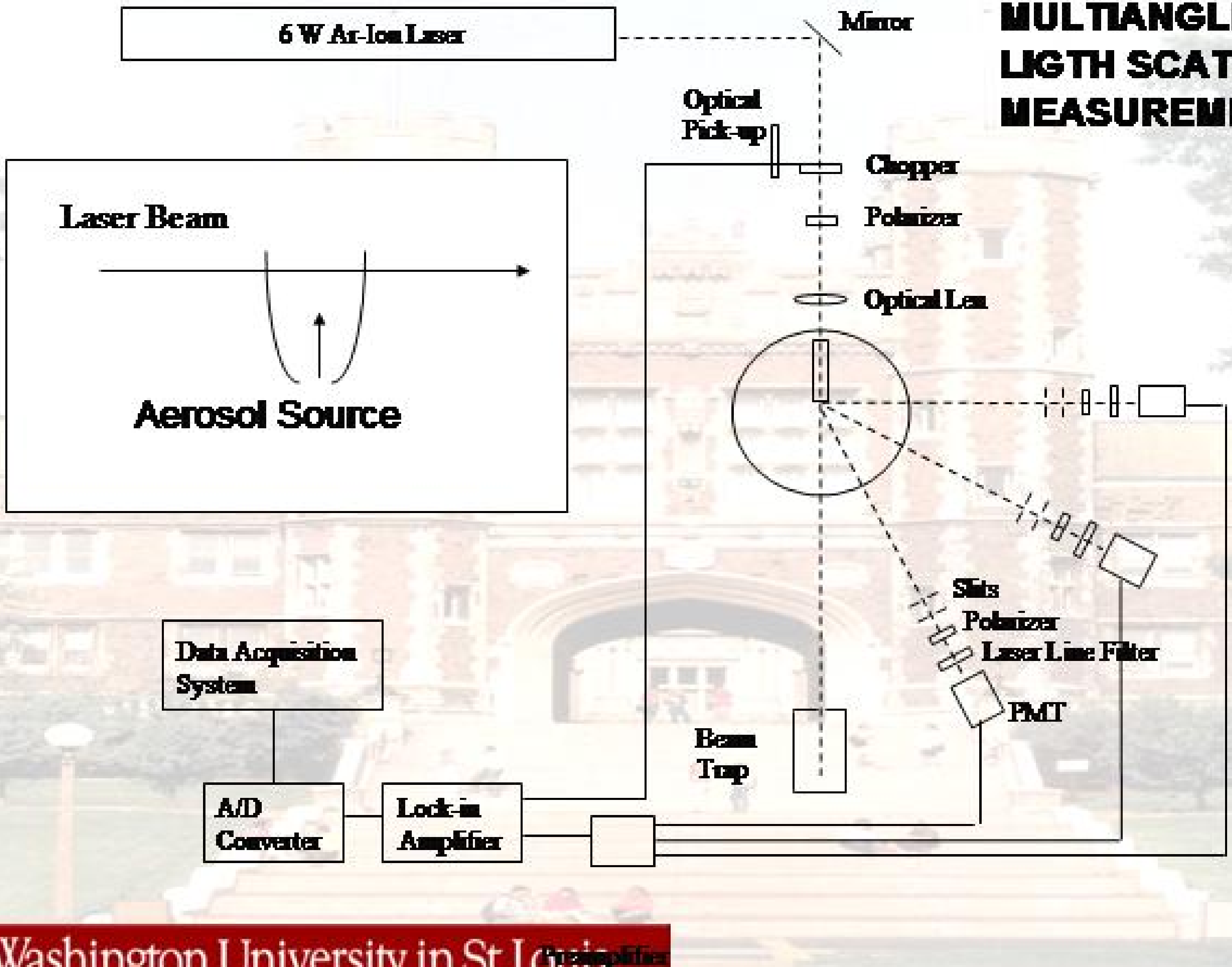
Rayleigh and Mie Scattering Theories

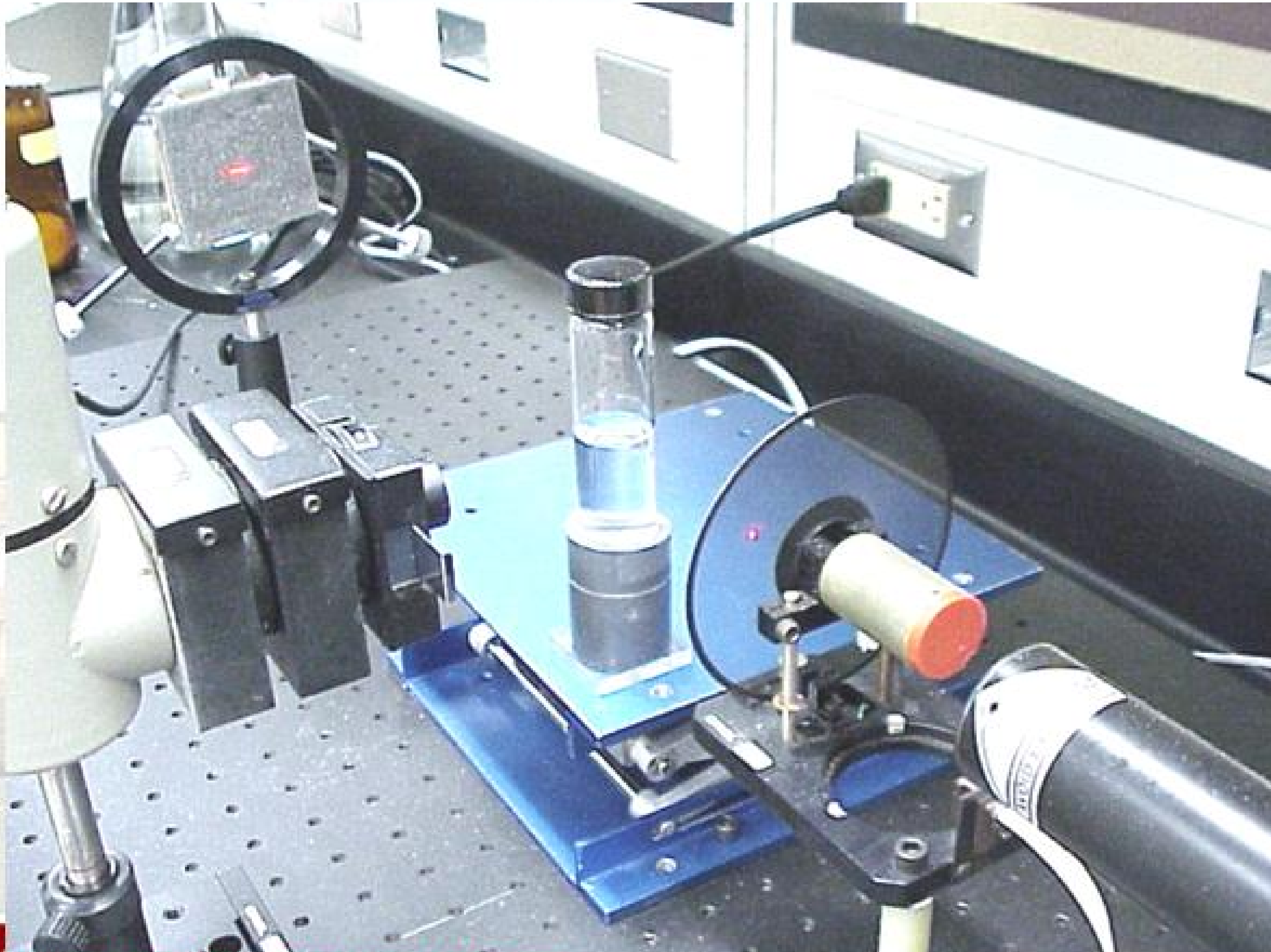


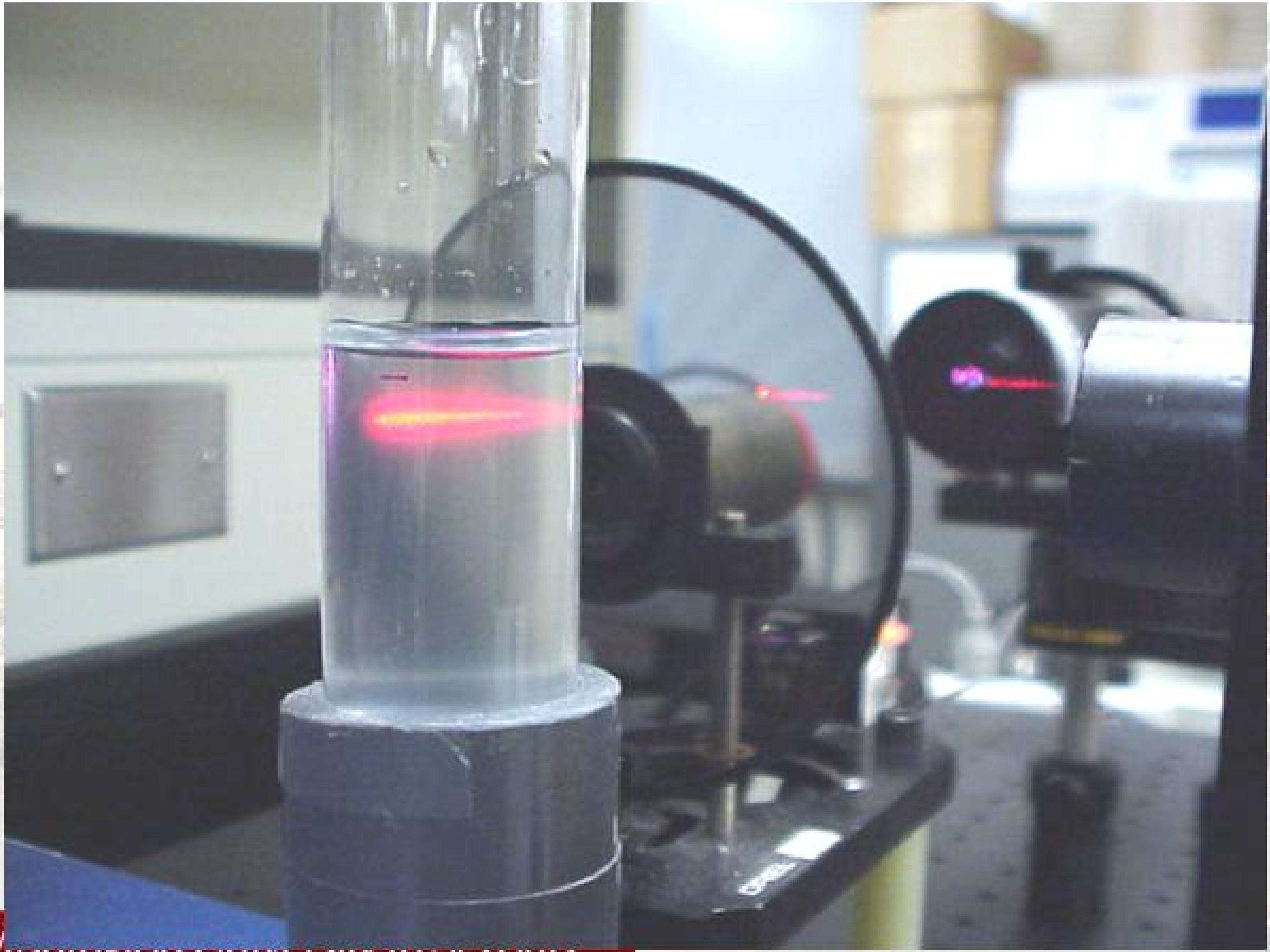
$$I(\theta) = \frac{I_0 \lambda^2 (C_{vv} + C_{hh})}{8\pi^2 R^2}$$

Scattered Intensity is a function of particle size, refractive index, angle of detection

MULTIANGLE LIGTH SCATTERING MEASUREMENTS



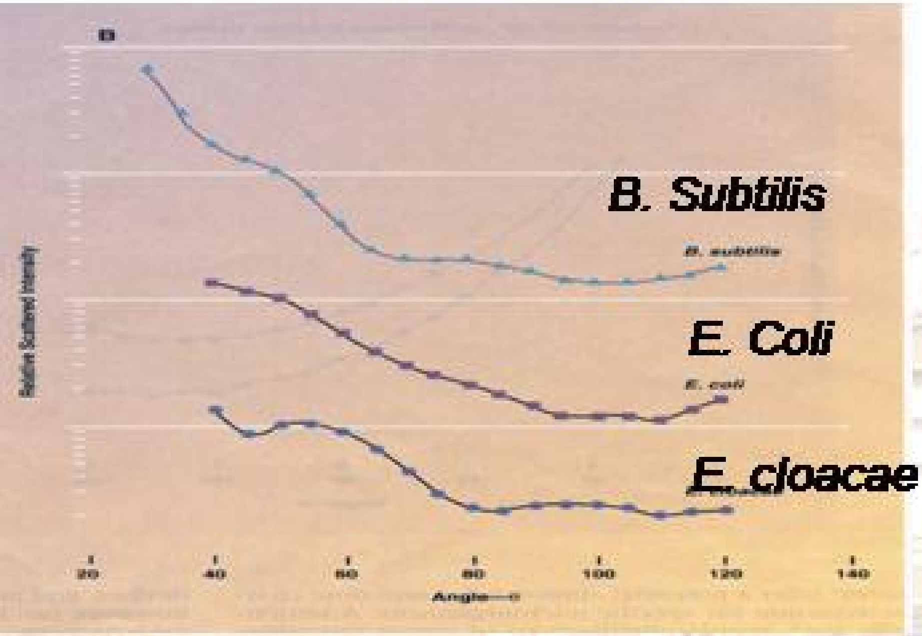




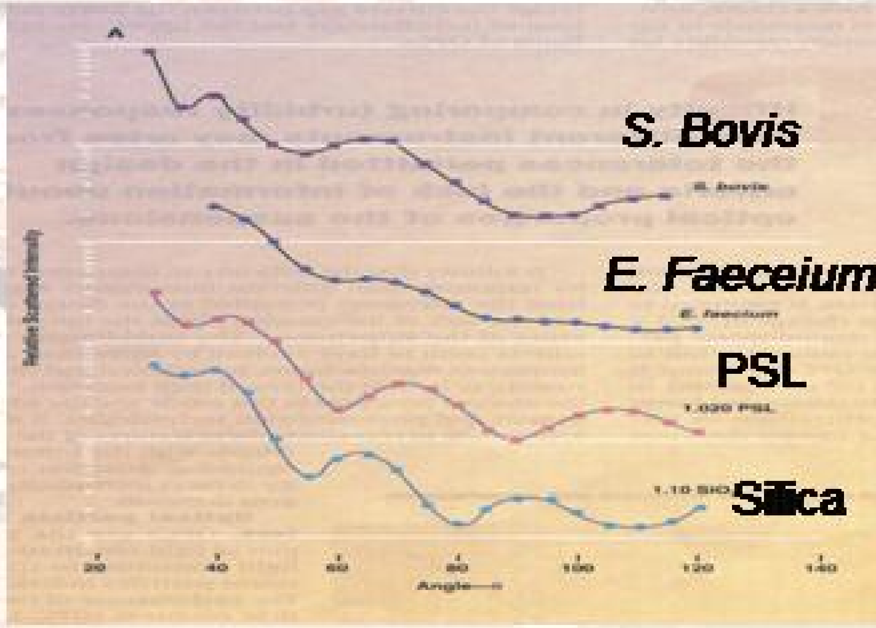
Detection of Micro-Organisms

- There is a renewed interest in quick and robust methods of detection of micro-organisms
- Laser based optical scattering systems offer a potential method of identifying larger bacteria – depending on shape, size and viability, they have unique light scattering patterns as a function of angle
- Can also modify to measure uv-vis absorption, or fluorescent signal to improve selectivity of detection.

ANGULAR DISTRIBUTION OF SCATTERED INTENSITY FOR ROD SHAPED MICRO-ORGANISMS



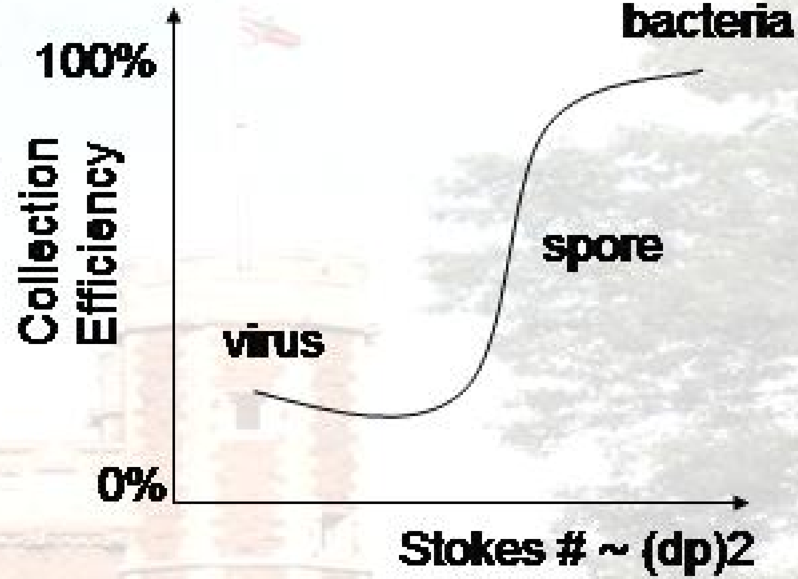
ANGULAR DISTRIBUTION OF SCATTERED INTENSITY – OTHER MICRO-ORGANISMS



DETECTION OF BIOLOGICAL PARTICLES

AGIs – How effective are they?

$$St = \frac{\rho_p C d_p^{\,2} U_0}{18 \mu L}$$



• AGI – Impinger designed for collection based on impaction of bioaerosols onto liquid surface

• Impaction efficiency increases with Stokes Number, St; which is proportional to square of diameter

•Bacteria which is in 1 to 10 um range Is 100 times larger than viruses. Hence St is 10,000 times smaller. Collection Efficiency is not going to be 100%

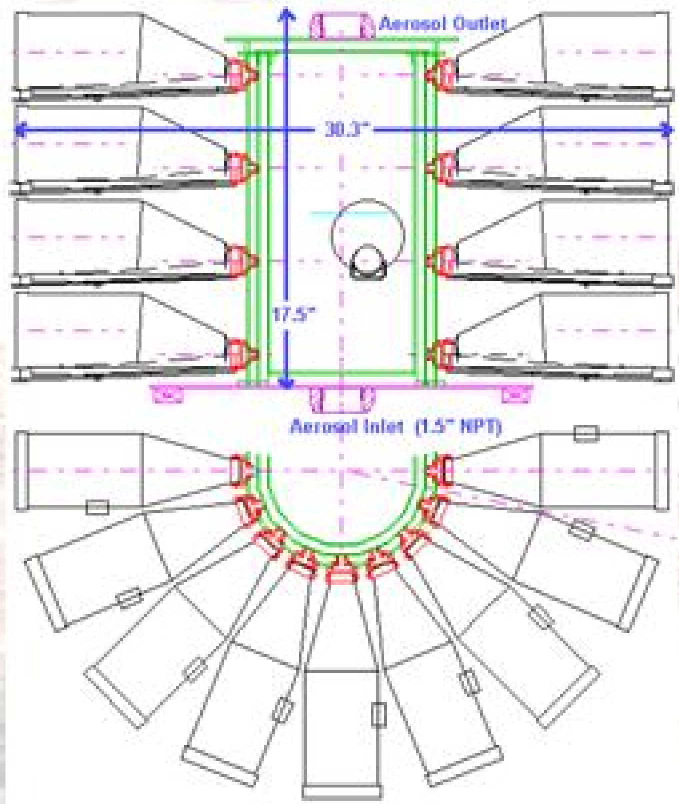
•Increasing velocity may help – but may alter viability of organism during collection

•Need to design more effective collection systems for viruses and fragments

Summary of Aerosol Measurement Devices

- Total particle counts – best instrument is the Condensation Particle Counter (CPC)
- Particles less than 100 nm – use the NanoDMA – CPC system
- Particles between 100 and 1000 nm – use the DMA (SMPS system)
- Particles greater than 1000 nm (1 um) – use Optical Particle Counters (OPC) or Aerodynamic Particle Sizers
- Characterize systems such as AGI's for the system in which they are to be used

Exposure chambers



- Is measuring the viable organisms by AGI' s at the outlet good enough to calculate dose??

- Due to complex flow patterns there is a spatial variation of aerosol concentration, and hence may have localized regions – especially near animal intake ports

- Have the tools to characterize this – both experimentally and theoretically!

Flow modeling, distribution in chamber

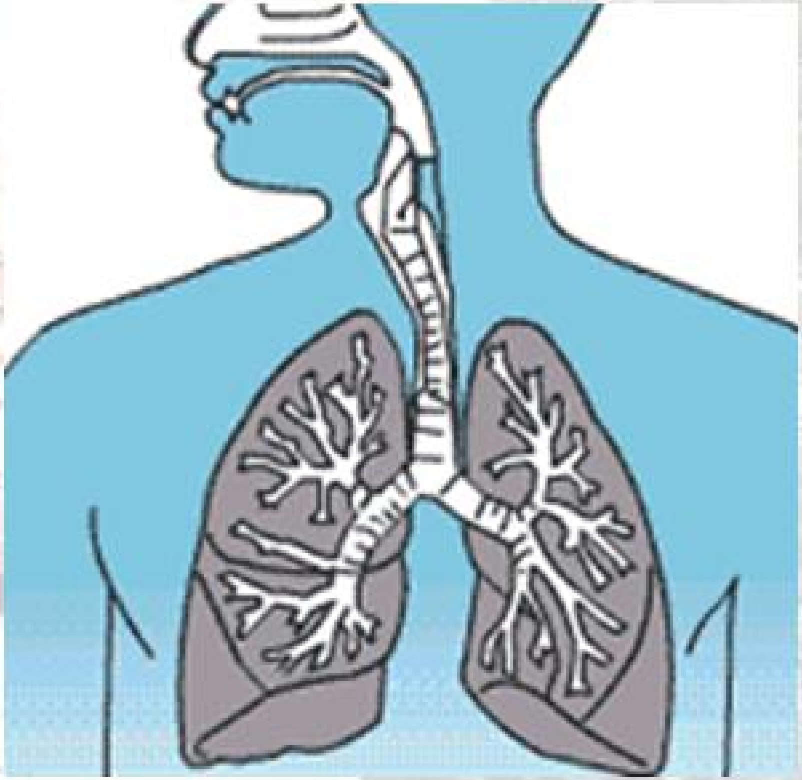
- Governing equation for particle transport

$$\frac{\partial n}{\partial t} = \underbrace{D\nabla^2 n}_{\text{Diffusion}} - \underbrace{\vec{u}\bullet\nabla n}_{\text{Convection}} + \underbrace{\frac{D}{kT}\nabla\bullet(\vec{F}_{EXT}n)}_{\text{External Forces}}$$

- Need flow field – can solve Navier Stokes equations, or use CFD codes
- Use velocity field, u, to solve particle size distribution, n, variation as a function of space and time
- Particle spatial distribution will be a function of size, geometry of chamber

Respiratory deposition

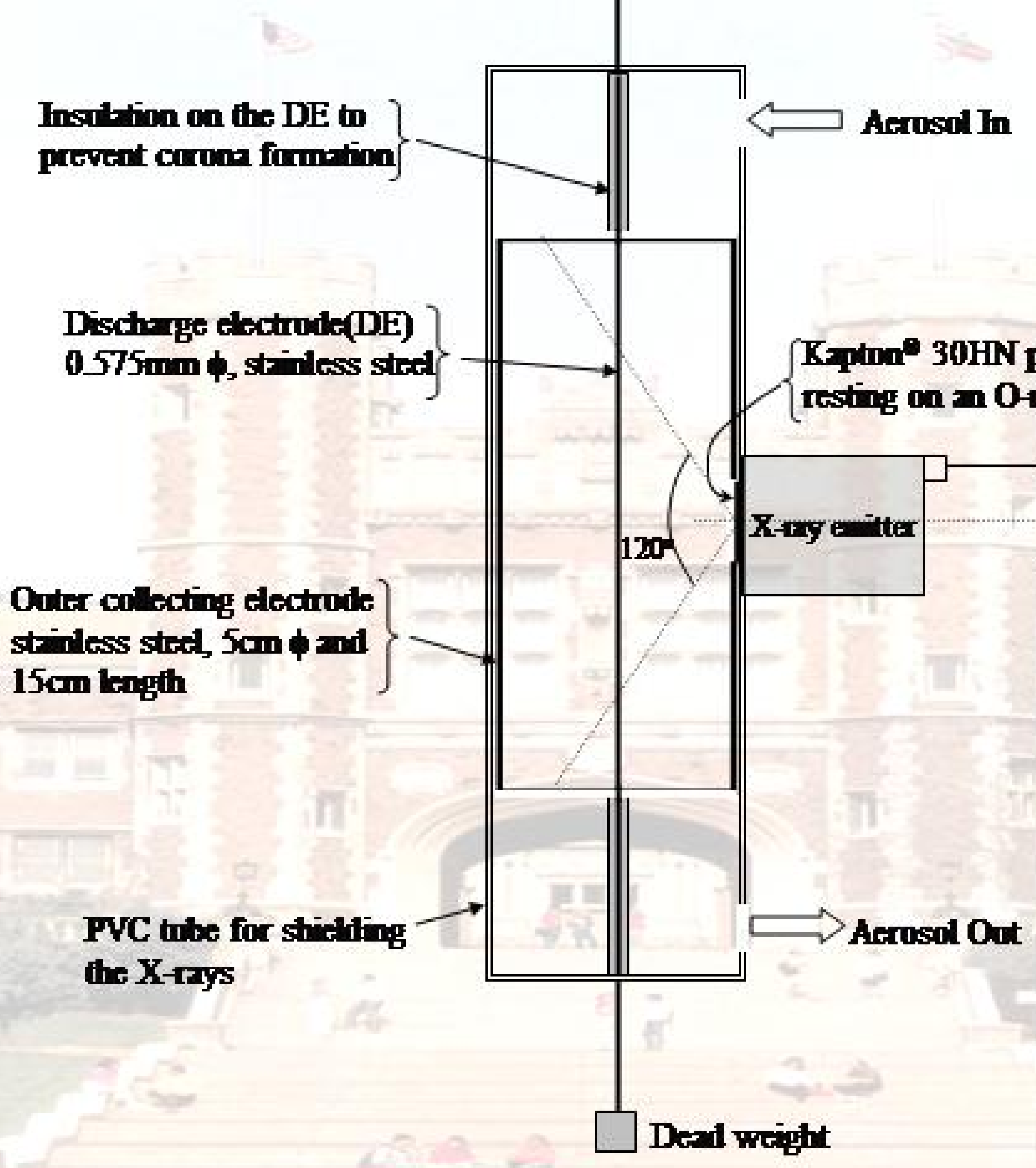
- Using spatial and time variation of size distribution function in respiratory chamber, can calculate size dependent deposition in respiratory system
- Importance of particle morphology (aggregates) and charge distribution very critical for accurate estimation
- http://www.aerosols.wustl.edu/aaqrl/courses/cycopcresp/



BIOAGENT INACTIVATION STUDIES: DEVELOPMENTAL PROJECT

- Capture and inactivation of bioagents, such as viruses and bacteria, from air streams important in many applications
  - Applications in aircraft cabin air filtration, indoor building ventilation systems, chem-bio agent inactivation (counter measures to bioterrorism)
- Several agents of interest – SARS virus, Small pox virus, spores, anthrax
- Several technologies in various stages of development (Alving, 2002). Most are based on filtration systems which are plagued with high pressure drops, maintenance and operational problems

NOVEL CORONA-SOFT XRAY SYSTEM FOR HIGH EFFICIENCY PARTICLE CAPTURE



* Existing particle control devices have a minima in collection efficiency in submicrometer & ultrafine size ranges
* Due to partial charging

US Patent Pending, 2002

- High voltage generates a corona, that produces an ion rich environment. Due to irradiation from Soft x-ray unit, there is a cascading effect that results in much higher ion concentrations
- Difficult to charge particles (ultrafine sizes) - are readily charged, and trapped in electrical field
- Due to high ion concentrations, and oxidizing environment, organic species are readily converted to carbon dioxide.
- Can further promote this with an nanostructured catalyst coating
- Very compact unit
- Can be readily mounted on existing duct work
- More than “4 to 5 logs” removal demonstrated for surrogates such as polio virus

Currently funded by the NIH Bio-Defense Project

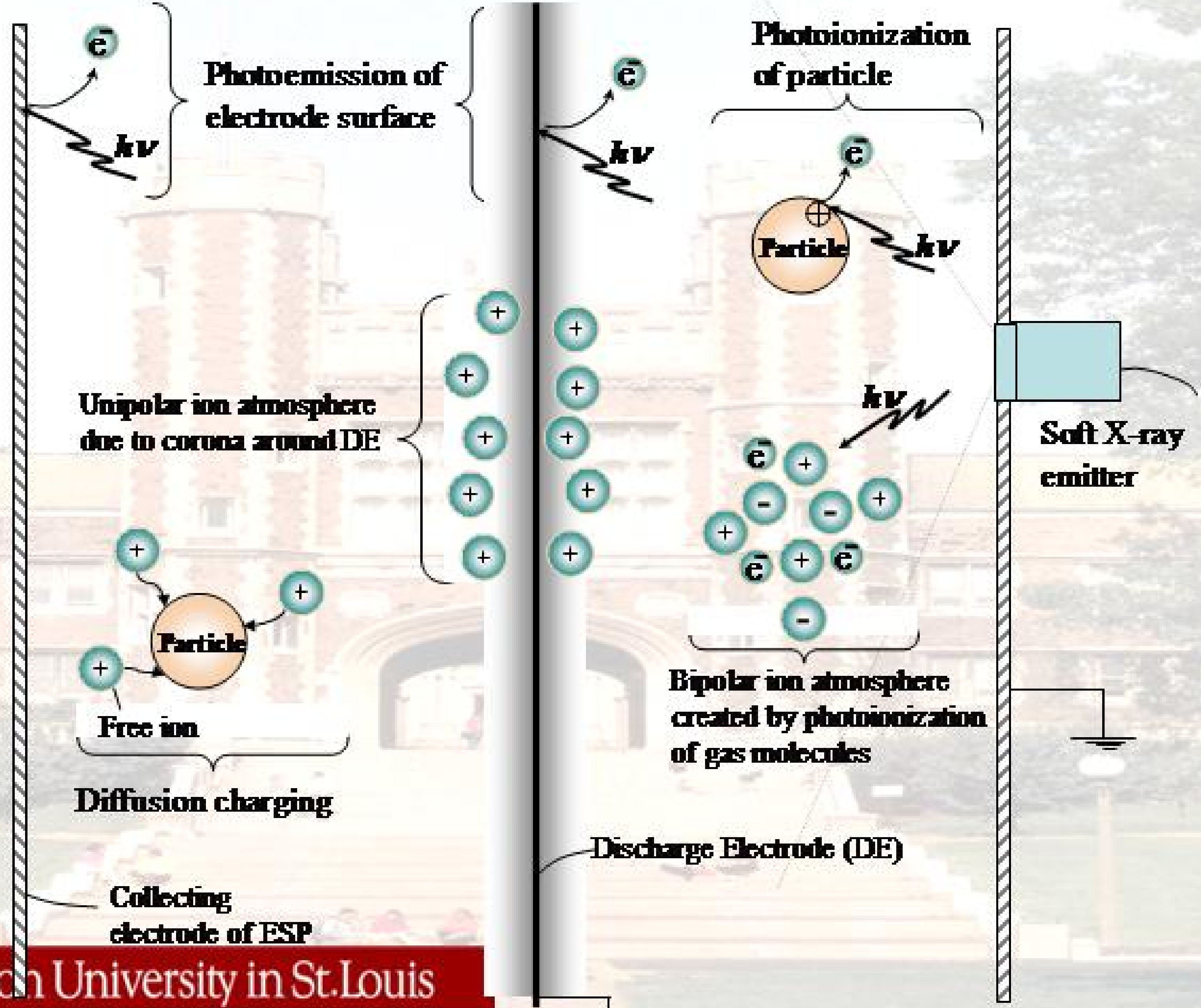
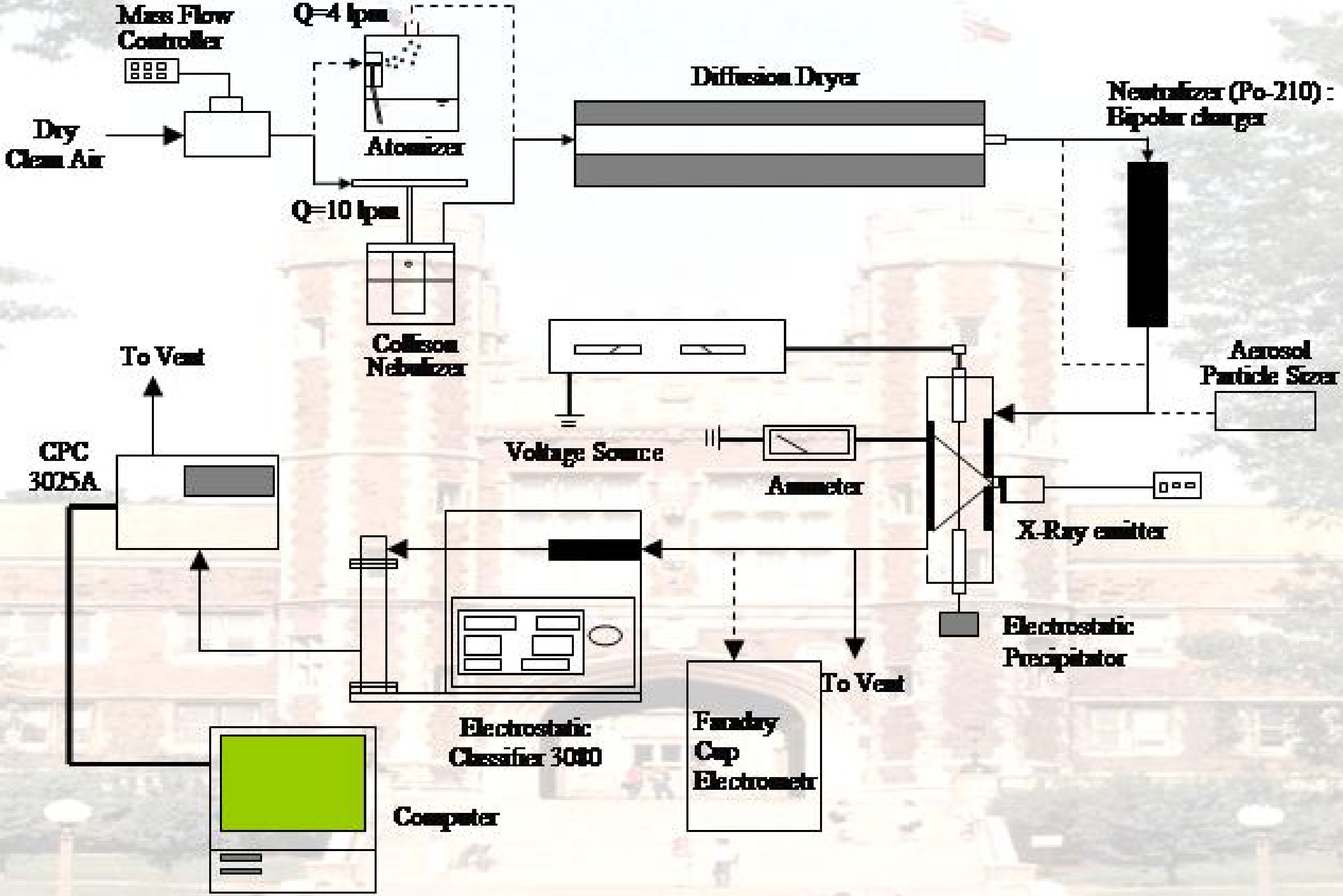
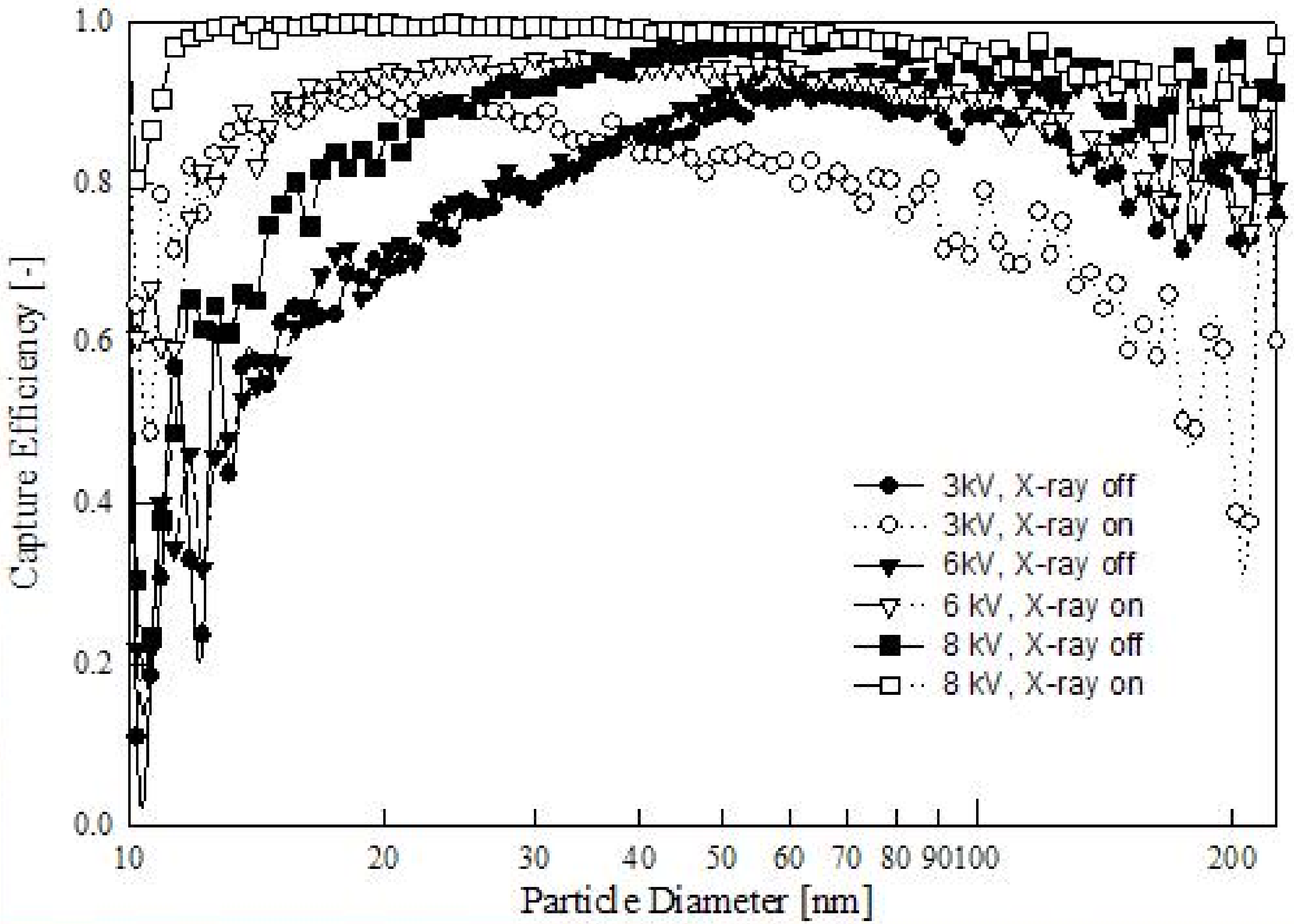

Photoemission of
electrode surface
Photoionization
of particle
Particle
Unipolar ion atmosphere
due to corona around DE
Soft X-ray
emitter
Particle
Free ion
Diffusion charging
Bipolar ion atmosphere
created by photoionization
of gas molecules
Discharge Electrode (DE)
Collecting
electrode of ESP

Figure 2



EXPERIMENTAL SYSTEM FOR AEROSOLIZING VIRUSES FOR CAPTURE TESTS IN CORONA-SOFT X_RAY UNIT

Capture efficiency at different particle diameters from 10 –225nm without neutralization with a Po-210 bipolar charger(Q=10lpm).



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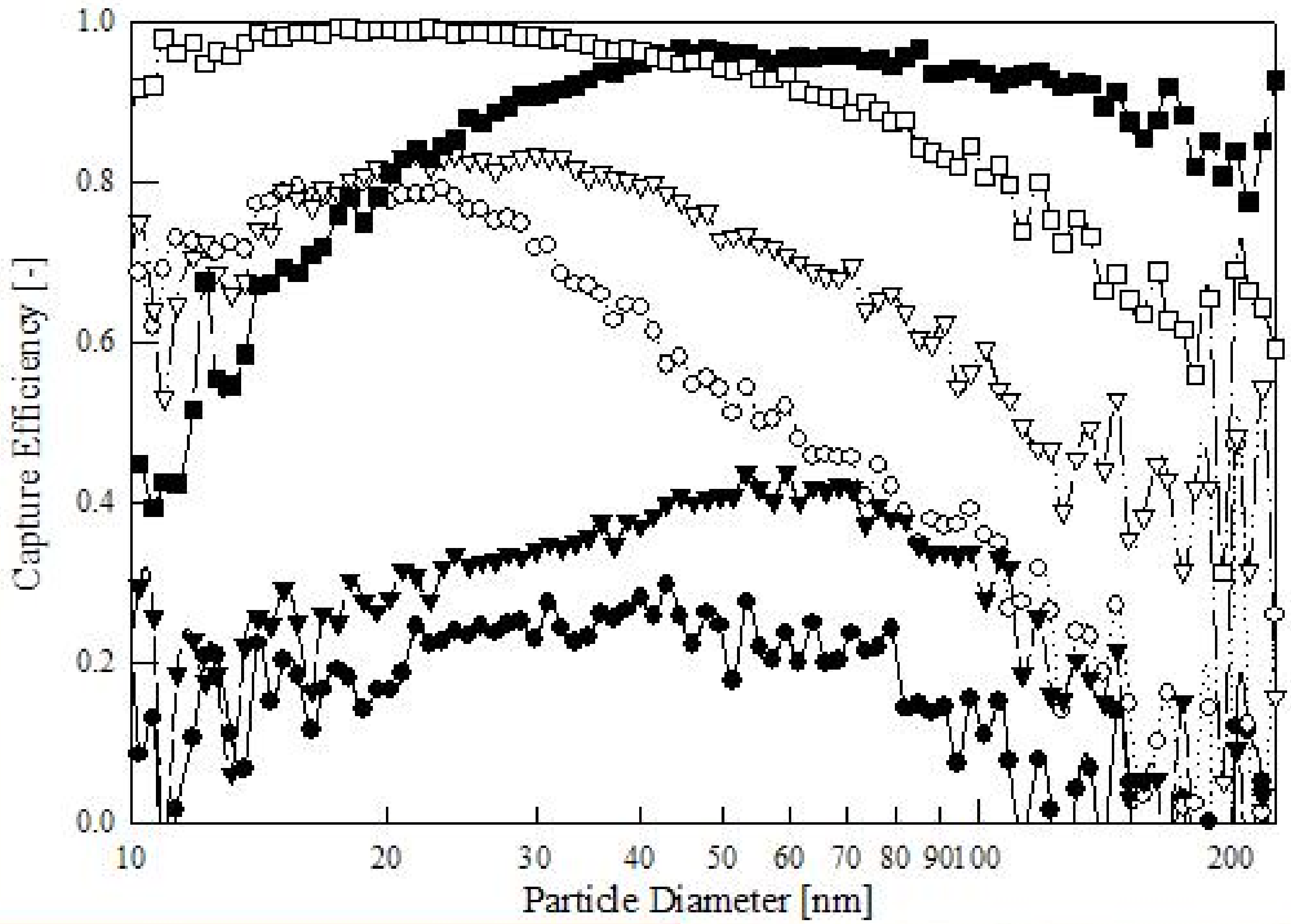
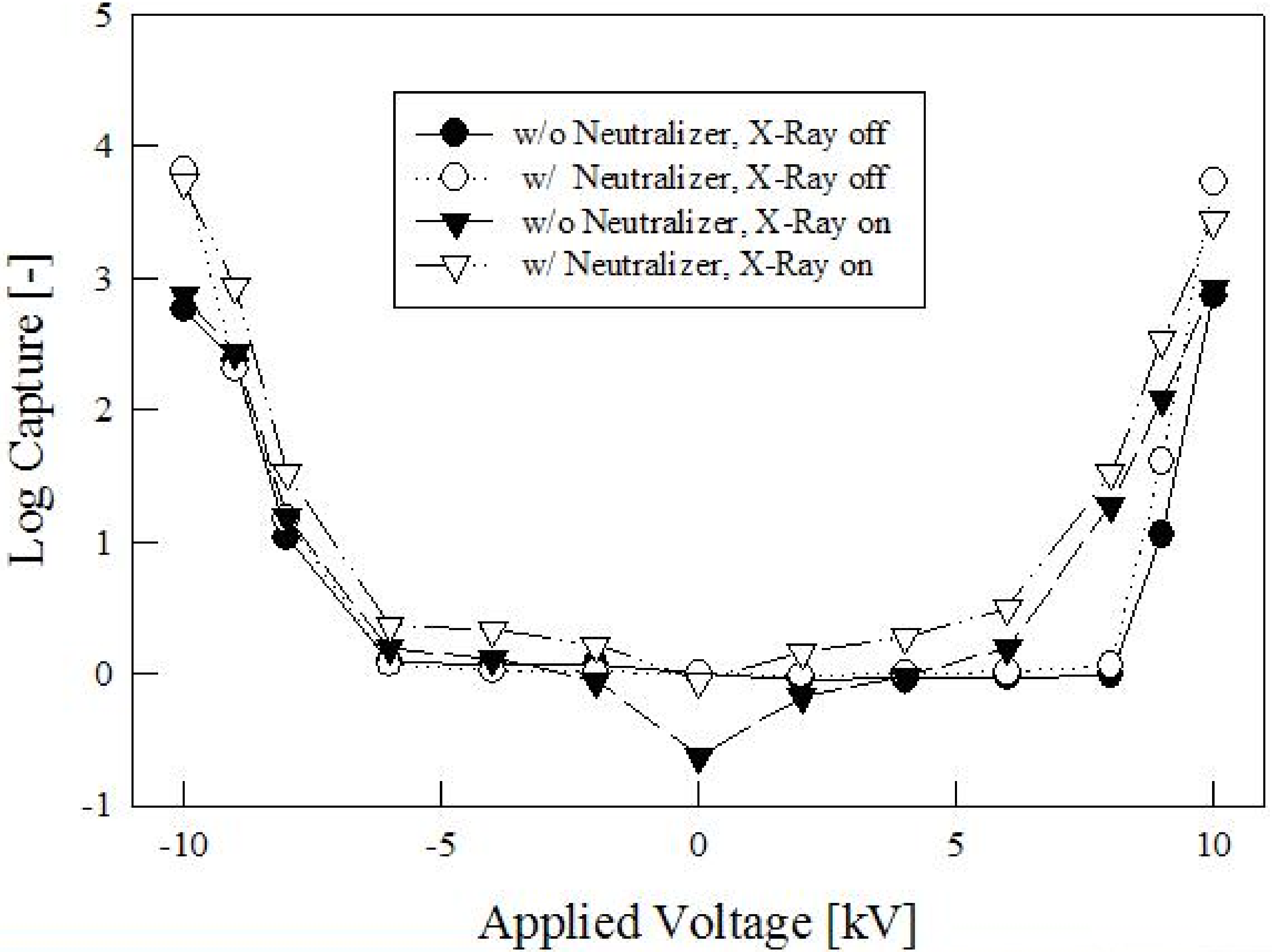


LOG CAPTURE OF VIRAL PARTICLES AS A FUNCTION OF APPLIED VOLTAGE



Aerosol aspects of aerobiology quite complex; but aerosol science and engineering is sufficiently advanced to address and resolve these issues.

Collaboration with main stream aerosol scientists strongly recommended

- Thank you for your attention

- Questions?

Aerosol and Air Quality Research Laboratory
Washington University in St. Louis
www.aerosols.wustl.edu/aaqrl

Particle Formation and Capture

SYNTHESIS & PROCESSING
- Aerosol Flame Reactors
- Aerosol Furnace Reactors
- Pristine and Doped TiO_2
- Nanostructured Coatings
- Magnetic Oxides

CONTROL & CAPTURE
- Soft X-Ray/Unipolar Coronas for Particle Charging & Capture
- Capture in Magnetic Fields
- Photocatalysis using TiO_2 – inactivation of bioaerosols and organic species
- Oxygen Enriched Coal Combustion/Hg Capture

Ambient Aerosols and Air Quality
- Diesel Engine Exhausts & Children's Health
- Morphology of Ambient PM
- Health Effects of Nanoparticles

Colloids/Bio-colloids
- Detection of Micro-organisms
- Electrostatic Filtration
- Inactivation of bio-agents

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AERODYNAMIC PARTICLE SIZER

- Particles are accelerated in a flow field
- Velocity is a function of the Stokes Number
- Use two laser system to time movement along a fixed distance, and then back calculate particle size
- Detection method good for large particles, as Stokes number goes as particle size^2. Can measure > 1 micrometer very effectively